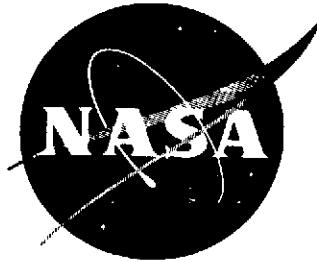


JSC-08571

NASA TECHNICAL MEMORANDUM

NASA TM X-58128  
November 1974



TECHNOLOGY EVALUATION OF HEATING,  
VENTILATION, AND AIR CONDITIONING  
FOR MIUS APPLICATION

**hudmius**

**MODULAR INTEGRATED UTILITY SYSTEMS**  
improving community utility services by supplying  
electricity, heating, cooling, and water/ processing  
liquid and solid wastes/ conserving energy and  
natural resources/ minimizing environmental impact



(NASA-TM-X-58128) TECHNOLOGY EVALUATION  
OF HEATING, VENTILATION, AND AIR  
CONDITIONING FOR MIUS APPLICATION (NASA)  
63 p HC \$4.25

CSCL 14B

N75-10135

Unclass

G3/14 52738

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS 77058

1. Report No. <b>NASA TM X-58128</b>		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle <b>TECHNOLOGY EVALUATION OF HEATING, VENTILATION, AND AIR CONDITIONING FOR MIUS APPLICATION</b>				5. Report Date <b>November 1974</b>	
				6. Performing Organization Code	
7. Author(s) <b>William L. Gill, Martin B. Keough, and James O. Rippey</b>				8. Performing Organization Report No. <b>JSC-08571</b>	
9. Performing Organization Name and Address <b>Lyndon B. Johnson Space Center Houston, Texas 77058</b>				10. Work Unit No. <b>386-01-00-00-72</b>	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address <b>National Aeronautics and Space Administration Washington, D. C. 20546</b>				13. Type of Report and Period Covered <b>Technical Memorandum</b>	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract  <p>This report is a first look at potential ways of providing heating, ventilation, and air conditioning for a building complex serviced by a modular integrated utility system (MIUS). Literature surveys were conducted to investigate both conventional and unusual systems to serve this purpose. The advantages and disadvantages of the systems most compatible with MIUS are discussed.</p>					
17. Key Words (Suggested by Author(s)) <ul style="list-style-type: none"> <li>* Air Conditioning</li> <li>* Ventilation</li> <li>* Heating</li> </ul>			18. Distribution Statement <b>STAR Subject Category: II.</b>		
19. Security Classif. (of this report) <b>None</b>		20. Security Classif. (of this page) <b>None</b>		21. No. of Pages <b>63</b>	
				22. Price*	

TECHNOLOGY EVALUATION OF HEATING,  
VENTILATION, AND AIR CONDITIONING  
FOR MIUS APPLICATION

William L. Gill, Martin B. Keough and James O. Rippey  
Lyndon B. Johnson Space Center  
Houston, Texas 77058

## PREFACE

This report is a brief survey of heating, ventilation, and air conditioning (HVAC) equipment that could be applicable for a modular integrated utility system (MIUS). It is one of a series of subsystem surveys prepared by the engineers of the Urban Systems Project Office (USPO) under the direction of Jerry Craig, Deputy Manager of USPO. A short, rigorous time schedule was established to obtain and compile this initial material so that maximum program emphasis could be placed on systems integration and optimization in MIUS. The report has two purposes: to familiarize USPO engineers with the state of the art in this field and to scan and document the types of equipment that appear most adaptable to MIUS applications. This report is not intended to be a quantitative, comprehensive, or exhaustive technology assessment but rather a compilation of first-look information considered significant by USPO engineers engaged in MIUS HVAC design. It represents the initial effort in a continuing technology evaluation of a vital MIUS subsystem. It is hoped that further results of these studies will be documented in later MIUS design and development reports.

PRECEDING PAGE BLANK NOT FILMED

## COORDINATED TECHNICAL REVIEW

Drafts of technical documents are reviewed by the agencies participating in the Department of Housing and Urban Development (HUD) MIUS Program. Comments are assembled by the National Bureau of Standards (NBS) Team, HUD MIUS Project, into a Coordinated Technical Review. The draft of this publication received such a review and all comments were resolved.

## CONTENTS

Section	Page
SUMMARY . . . . .	1
INTRODUCTION . . . . .	1
COOLING SYSTEMS . . . . .	3
Vapor Compression Refrigeration Cycle . . . . .	3
Vapor Absorption Refrigeration Cycle . . . . .	5
Compound Refrigeration System . . . . .	8
Cascade Refrigeration System . . . . .	8
Steam-Jet Refrigeration System . . . . .	9
Evaporative Cooling . . . . .	9
Thermoelectric Refrigeration System . . . . .	9
Cooling Systems Conclusions . . . . .	9
CENTRAL HEAT GENERATION/RECOVERY . . . . .	10
Heating Boilers . . . . .	10
Recovered Heat . . . . .	12
SPACE-HEATING SYSTEMS FOR BUILDINGS . . . . .	13
Fan Coil Units . . . . .	14
Electricity . . . . .	14
Gas Heaters . . . . .	14
Infrared Heating . . . . .	14
Solar Heating . . . . .	15
HEAT PUMP . . . . .	15
ENERGY CONSERVATION, USE, AND STORAGE TECHNIQUES . . . . .	16

Section	Page
HEAT REJECTION . . . . .	17
Cooling Tower . . . . .	17
Spray Pond . . . . .	18
Forced-Air Radiators . . . . .	18
Water Treatment . . . . .	19
Heat-Rejection Conclusions . . . . .	19
DISTRIBUTION SYSTEMS . . . . .	19
Air-Handling Systems . . . . .	20
Water Systems . . . . .	20
Heating/Cooling Modulation Techniques . . . . .	21
Distribution Systems Conclusions . . . . .	22
VENTILATION REQUIREMENTS AND TECHNIQUES . . . . .	22
HUMIDITY CONTROL . . . . .	24
Humidification . . . . .	24
Dehumidification . . . . .	25
Humidity Control Conclusions . . . . .	26
AIR FILTRATION . . . . .	26
ODOR CONTROL . . . . .	28
ELECTRICAL AND MECHANICAL CONTROLS AND EQUIPMENT . . . . .	29
NASA RESEARCH AND DEVELOPMENT TECHNOLOGY APPLICABLE TO THE MIUS PROJECT . . . . .	31
Thermal Control . . . . .	31
Thermal Energy Dissipation . . . . .	33
Environmental Control . . . . .	34
CONCLUDING REMARKS . . . . .	36

Section	Page
REFERENCES . . . . .	37
BIBLIOGRAPHY . . . . .	38
APPENDIX - ACKNOWLEDGMENTS . . . . .	39



# TABLES

Table		Page
I	TOTAL ENERGY FACILITIES . . . . .	43
II	THERMAL CONTROL TECHNOLOGY . . . . .	44
III	THERMAL ENERGY DISSIPATION . . . . .	45
IV	ENVIRONMENTAL CONTROL . . . . .	47
V	AIR PURIFICATION PROCESSES AND INSTRUMENTATION . . . . .	48

## FIGURES

Figure		Page
1	Block diagram of the MIUS HVAC . . . . .	49
2	Vapor compression cycle block diagram . . . . .	50
3	Schematic of basic absorption cycle . . . . .	51
4	Building complex supplemental heating block diagram . . . . .	52
5	Schematic of heat pipe . . . . .	53

# TECHNOLOGY EVALUATION OF HEATING, VENTILATION, AND AIR CONDITIONING FOR MIUS APPLICATION

By William L. Gill  
Lyndon B. Johnson Space Center

## SUMMARY

This report describes candidate heating, ventilation, and air-conditioning systems and major components associated with supporting these systems. The various types of air-conditioning machinery that are available for use in modular integrated utility systems (MIUS) are enumerated; the advantages and disadvantages, as applied to MIUS, are considered.

Heating boilers are discussed briefly because they will be used only to augment recovered heat from MIUS prime mover systems. Building space-heating methods including fan coil units, electrical heating, gas, infrared, and solar heating are also discussed. The use of the heat pump to provide both heating and cooling is examined. Other items considered are heat-rejection, air-distribution, and ventilation requirements and techniques together with humidity control, air filtration, and odor control. A brief discussion of overall system control requirements and NASA research and development technology applicable to this area concludes this survey of the state of the art.

A combination of compression and absorption air conditioning together with the use of recovered engine heat for space heating appears to be the most efficient means of supplying cooling in a building complex served by an MIUS.

## INTRODUCTION

The purpose of this report is to describe, qualitatively, the technology of modern air-conditioning systems. Air conditioning can be defined as a process of controlling, simultaneously, the temperature, humidity, cleanliness, and distribution of air. These factors

determine energy requirements for comfort heating or winter air conditioning and comfort cooling or summer air conditioning.

This technology description is written to relate air-conditioning systems to the modular integrated utility systems (MIUS) concept. Air-conditioning systems are designed to serve a dwelling complex as shown in figure 1. This technology assessment indicates the major components of the air-conditioning system and notes some of the aspects of (1) the state of the art, (2) hardware status, (3) number of installations and operating experience, (4) reliability and maintenance, (5) operational life, and (6) application to the MIUS concept.

The MIUS system provides comfort heating, cooling, and domestic hot water. Most of these requirements are met with heat recovered from the power-generation equipment and the solid-waste treatment process, but additional heat may have to be generated to meet all demands.

Energy for heating or cooling a dwelling unit must be transported by a distribution system from the MIUS. The energy is delivered by water pipes and electricity. At the dwelling unit, this energy is transferred by heat exchangers to the air.

Heat-recovery equipment salvages heat from other MIUS subsystems and makes it available for other uses. Sources of recoverable heat are the power-generation, incinerator, and sewage-processing systems. Consideration can be given to recovering heat from various building/household sources such as appliances, lighting, and hot water drains.

The heating, ventilation, and air-conditioning (HVAC) system may incorporate energy storage and conservation techniques. The primary function of the energy storage system will be to synchronize the availability of heat energy with the demands of the space heating/cooling and domestic hot water systems. The heat-rejection system rejects heat from the heat-recovery water loop and other heat loops.

Electrical and mechanical controls are provided to automate the operation of the HVAC to maintain a preselected environment within dwelling units, to provide for a malfunction detection alarm, and to meter critical operating parameters.

The humidity control system provides humidity control within the dwelling unit during all seasons of the year. Air filtration and purification are provided in the dwelling

unit. Filters are used for proper control of contaminants within the fluid loop.

Noise control techniques will be used to attenuate noise to levels consistent with human comfort. Details of design specifications are contained in references 1, 2, and 3. The odor control system will provide the capability of controlling odor within the dwelling unit.

Total energy systems were evaluated because of their similarity to the MIUS concept. A total energy system is one that generates electrical power and uses the recovered heat from the power-generation equipment for space heating, comfort cooling, and domestic hot water heating. Eight total energy sites inspected during the preparation of this report are described in table I.

In conducting this technology survey, several companies were contacted and visited. The discussions with these firms provided relevant information concerning the air-conditioning systems in use today and the applicability of these systems to MIUS. A listing of these contacts is given in the appendix.

## COOLING SYSTEMS

This section is a summary of various techniques used for comfort cooling a single dwelling or a dwelling complex.

### Vapor Compression Refrigeration Cycle

The vapor compression refrigeration machine is the most common type cooling system used throughout the United States today for residential and commercial comfort cooling and for food refrigeration. In the compression cycle, a mechanical compressor is used to compress refrigerant vapor from the evaporator and deliver it to the condenser where it is liquefied. The vaporization heat is absorbed by the condenser-cooling medium (water or air at normal temperatures). The liquid refrigerant is fed back to the evaporator through an expansion valve. In the evaporator, heat is absorbed from the thermal transport medium by evaporation of the refrigerant, then the cycle is repeated (fig. 2).

The key component of this system is the compressor. It can be open (external drive through a coupling belt) or hermetically sealed (compressor/motor in integral housing) and may be either a positive displacement or a centrifugal

type. The positive displacement compressor may be a reciprocating, rotary, or a helical rotary (screw) type.

Reciprocating compressors operate at low speeds of approximately 3600 rpm and are favored for cooling capacities below 200 tons. Centrifugal compressors operate in multiple stages at speeds of approximately 6000 rpm and are suited for capacities from 100 to several thousand tons. For large cooling demands, vapor compression refrigeration machines may use either reciprocating or centrifugal compressors.

In general, there are three methods of driving the compression units.

1. Electric motors are commonly used for smaller applications (individual units for residences and apartments) but are also found in large-capacity applications.

2. Diesel, natural gas, or gas turbines are used for installations where air-conditioning requirements are greater than 60 tons. Diesels typically deliver approximately 2 ton-hr of compression refrigeration per pound of fuel.

3. The steam turbine is used for apartment complexes that contain more than 2500 apartments. In this size plant, the steam turbine generation is sometimes used for power generation as well as for the air-conditioning compressor operation.

The advantages and disadvantages of the compression chiller are as follows:

#### Advantages

1. State of the art is well advanced.

2. Availability of the large variety of units provides for close matching for all applications.

#### Disadvantages

1. Hermetically sealed compressors are difficult to repair.

2. Some prime mover/compressor combinations are noisy.

3. Performance characteristics are readily available. Electrical operating energy requirements range from approximately 0.67 to 0.90 kWe/ton of air conditioning.

3. Compression units cannot be operated directly by recovered heat. Compression units do not operate smoothly over an entire load range.

4. Unit equipment costs range from \$130/ton at 120 tons to \$60/ton at 600 tons. (Installation costs must also be added to these estimates.)

### Vapor Absorption Refrigeration Cycle

In the vapor absorption refrigeration cycle, heat acts directly rather than through a prime mover to move the refrigerant through the machine. Absorption refrigeration machines available today use either lithium bromide and water or ammonia and water. In the lithium bromide/water combination, the water acts as a refrigerant and the lithium bromide (salt solution) acts as an absorbent; in the ammonia/water combination, ammonia is the refrigerant and water is the absorbent. Temperatures below 273 K (32° F) can be achieved with the ammonia/water cycle without freezing the refrigerant.

Both refrigeration systems have about the same coefficient of performance (COP) (0.60 to 0.67); that is, they require approximately 18 000 to 20 000 Btu of heat input per ton of refrigeration produced when used in an air-conditioning application. Because of refrigerant freezing, the lithium bromide absorption system cannot be used in applications in which the refrigerant temperature is below 273 K (32° F). The principal advantage of the lithium bromide system is that the pure absorbent material is nonvolatile. This characteristic permits a simple still to be used in the generator that separates the refrigerant from the absorber. In the ammonia cycle, which also requires a relatively pure refrigerant in the cooling loop, a fractional distillation generator is required. The system is therefore more complex and usually contains more heat-exchanger equipment. The lithium bromide cycle is usually favored for air-conditioning applications.

The operation of a typical commercially available absorption system using lithium bromide and water is shown in figure 3. Chilled water flowing from the conditioned air

space releases its heat to the refrigerant (water) in the evaporator tubes where the refrigerant evaporates and is attracted and absorbed by a strong lithium bromide solution that flows over the absorber, thus cooling the water tubes. The diluted solution at the bottom of the absorber is pumped through a regenerative heat exchanger to the generator. This diluted solution flowing over the hot generator tube (heat energy source) is vaporized, thus concentrating the solution. This concentrated solution flows by gravity and pressure differential through the regenerative heat exchanger to the absorber section. Refrigerant vapor released in the generator flows to the condenser where it is cooled and condensed. Condensed refrigerant flows by gravity and pressure differential through a restrictor to the evaporator, and the cycle is repeated (fig. 3).

Absorption units are available in sizes ranging from approximately 100 to 1600 tons. The absorption equipment now available represents more than one-fourth of all the refrigeration units sold in the 100-ton and larger capacities.

The absorption unit is in widespread use with diesel engine power-generation equipment. The heat recovered from the engine and supplemental heat from boilers are used to operate single-stage absorption units. Using steam ( $1.03 \times 10^5$  pascals (15 psig)) to operate the single-absorption units requires approximately 18 000 Btu/ton of refrigeration based on typical absorption units currently in production. Absorption units are also operated with high-pressure hot water at approximately 394 to 422 K (250° to 300° F). One manufacturer, the Arkla Air Conditioning Company, advertises a unit that can be operated with inlet water temperatures of 372 K (210° F) and with a COP of 0.65. A review of other manufacturers' (Trane, York, and Carrier) catalogs indicates that their units will also operate at these off-design points; however, operating in the low-temperature regime results in less heat transfer in the generator. At typical coolant outlet temperatures of 277 to 279 K (40° to 44° F), the capacity of these machines is reduced to approximately 70 percent of those operating with  $1.03 \times 10^5$  pascals (15 psig) steam. Corrosion effects usually limit the exhaust temperature in heat-recovery equipment to 422 K (300° F) or higher; therefore, lowering the operating temperature of absorption refrigeration units will not in itself result in more heat being recovered from the prime movers. There should be a higher capital cost associated with operating equipment at lower temperatures because of their inherent lower capacity and because larger heat exchangers must be used in their generator sections.



Recently, two-stage or double-effect absorption air conditioners have been made available by one U. S. manufacturer, and other companies may soon offer similar equipment. These two-stage machines operate nominally on  $7.58 \times 10^5$  to  $8.62 \times 10^5$  pascals (110 to 125 psig) steam. The corresponding operating temperatures are 449 to 460 K (350° to 370° F). These machines operate with a COP ranging from 0.85 to 0.95 and require a heat input of 14 000 to 12 600 Btu/ton. Information in the Trane catalog indicates that the machine will operate at steam pressures as low as  $3.45 \times 10^5$  pascals (50 psig) or approximately 422 K (300° F). Capacity is reduced by approximately 60 percent under these conditions. The higher operating temperature of the refrigeration unit will result in lower heat recovery in a prime mover exhaust-recovery system because of the higher temperature steam requirements of the double-effect machine compared to the single-effect unit. Preliminary estimates indicate an increase of 10 to 15 percent in the amount of refrigeration produced by double-effect absorption refrigeration units operating at nominal conditions from waste-heat-recovery boilers compared to single-effect machines. Capital cost estimates are not available at this time for performing trade-off analyses between single- and double-effect machines. In general, double-effect machines do not produce a very much larger amount of refrigeration per unit of available recoverable heat from prime movers, and a trade-off study will be needed to evaluate both power and capital costs of competing single- and double-effect systems considering all equipment from heat-recovery to heat-rejection systems.

The advantages and disadvantages of the absorption chillers are as follows:

#### Advantages

1. Waste heat from electrical power generation in the form of low-pressure steam ( $1.03 \times 10^5$  pascals (15 psig)) or high-temperature water (394 K (250° F)), approximately, can be used as the primary energy source to run single-effect absorption machines.

#### Disadvantages

1. Efficiency is jeopardized when waste heat quantity becomes marginal.
2. Sensors and automatic controls are necessary for carefully controlling operating temperatures to meet acceptable performance levels.

2. Complete automatic controls provide for smooth throttling characteristics throughout the entire range from 0- to 100-percent capacity.

3. The chillers provide for rapid responses to load changes and are quiet and free of vibration.

4. The simple design results in a longer operational life than that of a compression unit.

5. A safe and inexpensive refrigerant (water) and a permanent, nontoxic, nonflammable salt or absorbent can be used.

6. The costs are competitive with compression units. The equipment costs range from \$145/ton at 120 tons to \$80/ton at 600 tons, free on board at the manufacturer's plant.

3. Excessive leak control is necessary to maintain good performance under full and partial load conditions.

4. Corrosion problems result from the use of lithium bromide salts.

5. Freezing is a potential problem if the evaporator temperature gets too low.

### Compound Refrigeration System

In compound systems, two or more compressors are combined in series, thus providing the capability of reaching lower temperatures than possible with one compressor. In general, these compound systems are for heavy-duty service and are not the type required for MIUS use.

### Cascade Refrigeration System

In this system, two or more condensing units are connected in series. Because cascade systems are used primarily in industrial processes in which it is necessary to cool objects or space to temperatures considerably below zero, they are not applicable to MIUS requirements.

## Steam-Jet Refrigeration System

The steam-jet refrigeration system is basically a compression system using a steam ejector to vaporize water at low pressure and to compress the resulting vapor. The water remaining in a liquid state after vaporization is chilled and can be used as a refrigerant. Because the high-pressure steam delivered to the ejector must be condensed together with the vapor resulting from the evaporation, the amount of heat to be rejected is two or three times greater than that rejected in the mechanical refrigeration cycle. Using a condensing temperature of 311 K (100° F) and a chilled water temperature of 281 K (45° F), a steam consumption of 26 lb/ton-hr is typical of the comfort cooling application when using  $6.89 \times 10^5$  pascals (100 psig) of saturated steam. Attempts to adapt the heat-injector cooling system to trucks and automobiles were abandoned because system efficiencies were too low. This system, therefore, does not appear to be adaptable to MIUS requirements.

## Evaporative Cooling

In this technique, air is cooled by allowing water to be evaporated into it. As the water changes to vapor, the latent heat of vaporization is extracted from the surrounding air. In those areas where it is climatologically feasible (i.e., dry, arid climates), this technique is in common use, and hardware is economically available. Evaporative cooling should always be considered for MIUS in those locations where a hot, dry climate is encountered.

## Thermoelectric Refrigeration System

In this system, the Peltier effect is used to pump heat directly with electricity. Compared with conventional compressor units, this refrigeration system has a low thermal efficiency. The primary application has been for comfort cooling of nuclear submarines. Even with the latest advancements developed by Government funding and research, the cost of the thermoelectric equipment is significantly more than the absorption or compression equipment.

## Cooling Systems Conclusions

The absorption unit is desirable for cooling systems because high-temperature water or low-pressure steam can be

used directly; thus, it is the only system available for using recovered heat from the power-production system. This machine can be used in relatively small applications. The compression units are normally powered by an electric motor for small capacity plants; in larger sizes, steam or diesel engines can be used to drive the compressor.

The physical size of the absorption unit is normally larger than the compression unit because a relatively large evaporation unit is needed. In a system where space is critical, this size may be a significant disadvantage. Both the compression and absorption units are readily available in the capacity ranges being considered for MIUS. Reliability of the absorption unit is generally higher than that of the compression unit, and the absorption unit requires less maintenance because it contains fewer moving parts. Based on these considerations, it appears that combinations of both the compression and the absorption units are prime candidates for MIUS use.

## CENTRAL HEAT GENERATION/RECOVERY

Comfort heating or winter air conditioning can be accomplished by heat transfer from an energy source to a conditioned air space.

### Heating Boilers

Heating boilers are classified in two general groups: (1) sectional cast-iron boilers (fire tube) and (2) steel firebox boilers (water tube). Cast-iron boilers are normally limited to  $1.03 \times 10^5$  pascals (15 psig) steam pressure and  $2.07 \times 10^5$  pascals (30 psig) water pressure at a temperature of 410 K (279° F) with an output ranging to 2 500 000 Btu/hr. Most modern fire-tube units operate at or below  $1.72 \times 10^6$  pascals (250 psig) and below approximately 9100 kg/hr (20 000 lb/hr) of steam. Modern water-tube packaged units have steam capacities as large as 27 200 kg/hr (60 000 lb/hr) and pressures as large as  $6\,200\,000$  pascals (900 psig). Fuels for the fire-tube and water-tube boilers may be oil or gas or a combination of these. Cast-iron boilers are also designed to operate with coal.

Cast-iron steel boilers are suited for low pressures (less than  $1.03 \times 10^5$  pascals (15 psig)), and a licensed operator is not required during the operation of boilers at pressures less than  $1.03 \times 10^5$  pascals (15 psig). These boilers are used principally in small heating and industrial

plants. Both fire-tube and water-tube steel boilers can supply high-pressure steam. High-pressure steam boilers are readily available in sizes and ratings to meet MIUS requirements but generally are used in special jobs in which hot water or other types of heating are not practical. Steam heating can be affected by a one-pipe distribution system in which the condensate returns in the same pipe; however, the two-pipe system (condensate returns in a separate pipe) is more common. One method for estimating the capital cost of low-pressure boilers is the boiler rating (in MBtu/hr) plus 400 equals the cost of the boiler. Thus, an 800 MBtu/hr boiler is estimated to cost approximately \$1200. This estimate is for a cast-iron boiler based on 1968 pricing.

Steel boilers may be the fire-tube or water-tube type. In the fire-tube boiler, the hot gases pass through tubes that are surrounded by water as opposed to the water-tube boiler where the water passes through tubes that are surrounded by hot gases. Because of the large amount of water contained in the fire-tube boiler, the boiler provides some reserve storage and never yields better than average performance under fluctuating load conditions. Both types of boilers can be designed with integral water-jacketed furnaces or provided with refractory-lined brick fire-box walls. Steel boiler capacities range from those required for small residences to approximately 23 500 MBtu gross output.

The use of steam for heating is not the preferred method because such systems are noisy, require traps and other extra equipment, and usually have higher maintenance costs than water systems. Steam can augment recovered heat input to absorption refrigeration, however. In the hot water systems, temperatures range from 355 to 478 K (180° to 400° F). The two basic hot water system types are direct and indirect.

In the direct system, an expansion tank is provided to expand water as it leaves the boiler. This hot water is then pumped through a distribution system to the air space heat exchanger and back to the boiler for reheating. In the indirect system, steam in a heat exchanger raises the circulating heating water to within a few degrees of the steam temperature. The hot water is then pumped through the distribution system and back to the heat exchanger.

One concept that should be considered is the use of a series of smaller boilers instead of a few large ones. In using multiple boilers, all boilers can run online at maximum thermal efficiency. They are also highly reliable and easy to maintain. Typically, oil- and gas-fired units

have a thermal efficiency of 75 to 80 percent at rated load. Some of the advantages of using hot water boilers for MIUS are as follows:

1. Easily available in wide temperature range
2. Serve as a versatile heat exchanger that can be compatible with various forms of energy, including waste heat
3. Low maintenance because the operating conditions are not extreme
4. Adapts to domestic hot water requirements
5. Fewer corrosion problems than with a steam system

Consideration has to be given to the water treatment, water makeup, and blowdown of the boiler system. Multipurpose liquid treatments designed to control sludge, corrosion, and scale formation are used in modern water treatment for boilers. The blowdown of the boiler may be based on a conductivity measurement that is an indication of the concentration of dissolved solids. When this concentration reaches a specified level, the boiler is blown down; that is, some of the boiler water is drained off and fresh water is added. The blowdown effluent is high in dissolved solids and may be difficult to treat adequately in the MIUS water-treatment system. Therefore, an alternate method of disposing of this effluent may be necessary.

#### Recovered Heat

To conserve energy, heat will be recovered within the MIUS and reused whenever practical. The primary sources of this MIUS heat are from power-generation and waste-incineration equipment, and the major uses are for space heating, domestic hot water heating, and absorption comfort cooling. Potential uses for this recovered heat may be in the areas of waste preconditioning and water treatment. The techniques used in the recovery of this waste heat are discussed in the following paragraphs.

Thermal energy can be recovered from internal combustion engines in the form of steam or hot water. Because the operational characteristics of the hot water system have not been clearly defined, the steam system is in more common use. The availability of heat-recovery equipment for hot water systems is also much more limited than for steam systems. For several reasons, a hot water system is more desirable in some cases than a steam system.

In some internal combustion engines, block coolant is discharged at a temperature below 367 K (200° F). In the steam systems, the engines operate at approximately 389 K (240° F). The maintenance of a hot water system is usually less than that of a steam system because the lower operating temperature results in less damage to seals and valve seats. In a steam system, hotspots can develop in the engine and cause engine failure.

Low-grade heat (approximately 311 K (100° F)) may also be recovered from the comfort cooling system and the lighting system. This heat is not sufficient for space heating but can be used for preheating and reheating the domestic hot water or preheating ventilation air. One example of low-grade heat recovery is evidenced in the Westinghouse offices in Pittsburgh, Pennsylvania in which heat is recovered from the lighting systems by a circulating water system and used to preheat the domestic hot water.

Recovering energy from various sources within a building complex may be considered for MIUS. The energy can then be used for other processes or stored for later use. Potential energy sources include appliances such as ranges, refrigerators, and freezers; lighting systems; hot water usage (dishwashers, showers, and clothes washers); clothes dryers/furnace exhaust; and outlet ventilation air. This recovered energy can then be used in the preheating of domestic hot water and in heating space, sidewalks, and swimming pools.

In general, the recovery and use of heat from domestic processes has had little or not attention in present building systems design. However, recent studies (refs. 4 and 5) identify domestic processes as potential sources of significant energy savings. The optimum system for satisfying the total thermal requirements of a dwelling unit consists of a combination of waste heat recovery and heat generation from water.

## SPACE-HEATING SYSTEMS FOR BUILDINGS

Because a building space-heating system must use the recovered heat from the power-generation equipment and other MIUS sources, it must use some type of fan coil unit to transfer the heat from the heat-recovery medium to the dwelling unit space. The fan coil heating system and other space-heating techniques and applications to the MIUS concept are discussed in this section.

## Fan Coil Units

Fan coil units are placed in the air-handling ducts and transfer thermal energy from the hot water to the air through finned tubes. This heating method is in widespread use today in industry as well as in buildings with total energy systems.

## Electricity

In assessing the applicability of electric heating to an MIUS installation, there are two points of consideration: is this technique practical for total heating requirements or should it be a supplemental heating source? From an energy conservation standpoint, it is obvious that the electric heating technique is applicable to MIUS only for supplemental heating (fig. 4).

Compact electric heating units have been installed in main supply or branch ducts of central-fan steam and water systems to provide the final temperature and relative humidity required for comfort or process air conditioning. Electric heating systems are frequently used where electrical power is inexpensive. There are many advantages of electric heating. The operation is extremely simple, versatile, easily controlled, and clean at the point of use; however, the amount of emissions at the point of generation could be higher than that from a local heating plant. The operation is safe because there is no open flame.

## Gas Heaters

Gas-fired air heaters can be installed directly in the ventilation system of the building to be heated, whereas combustion gases must be vented to the environment. Heating units are inexpensive and readily available. Because the MIUS concept dictates the use of recovered heat, gas heating is best suited for supplemental heating use (fig. 4).

## Infrared Heating

In a gas infrared heater, a material of high emissivity is heated to a high temperature and becomes a radiant heat source. An air/gas mixture is distributed uniformly over the rear of the ceramic mat. As it passes through the holes in the ceramic, the mixture burns just below the front surface of the ceramic so that the surface of the ceramic is heated to 1172 K (1650° F).



In some installations, the gas-fired infrared heaters are mounted overhead to direct radiation toward the floor. Infrared heating may be used for supplemental heating in an MIUS.

### Solar Heating

The solar flat-plate collector can be used to heat domestic hot water. Most solar water heaters use the thermosyphon principle to circulate water between the heat-collection area (flat plate) and the storage tank without moving parts. Dust on the collectors, cloudy weather, and clogging and scaling of pipes have been the main problems in using flat-plate collectors; however, since World War II, materials and construction have been improved. Solar water heaters are widely used in Africa and in the Mediterranean area where sunlight is abundant. Unknown climate at the site location make solar heaters questionable for universal MIUS application.

### HEAT PUMP

Another energy conservation practice not previously discussed in connection with heat rejection or heat is the use of a heat pump. The heat pump is a year-round comfort air-conditioning machine that supplies cooling and heating. The heat pump is a reversible system that moves heat in either direction. This allows heat from some external source to be delivered to the building during the heating cycle or, conversely, the removal of building heat to an external sink in the cooling phase. Generally, the thermal cycle is identical to that of an ordinary refrigeration process except that the evaporator and condenser can exchange functions. Cycle changeover is accomplished by valving, which reverses the process.

The three basic heat pump types are air to air, water to air, and water to water. Although the air-to-air heat pumps are the most common, they are limited by their heating capability during cool seasons. Additional heat can be supplied to extend their operation area, but economical use of these heat pumps is generally limited to areas where the summer cooling load approximately equals the winter heating load. In water-to-air and water-to-water heat pumps, the added energy-storage capability of water is used for heat recovery or rejection. Ponds, lakes, rivers, and wells are some of the water reservoirs that have been used to provide the heat pump cycles with a heat sink or source, thereby extending their area of practical operation.

The heat pump appears to be an excellent energy conservation system for MIUS applications because a low-temperature thermal loop from an MIUS central plant can be used as a heat source. Because applicable equipment is in limited use, a complete technology assessment has not been attempted.

## ENERGY CONSERVATION, USE, AND STORAGE TECHNIQUES

Extensive use of energy conservation techniques is the ultimate challenge to a successful MIUS program. Heat rejection, energy storage, and heat-recovery systems must be used harmoniously throughout the year. New conservation methods must be continually investigated and introduced into the design wherever practical. If energy storage can be used, other equipment can be smaller because it is sized to meet average rather than peak demands.

Thermal energy is not generated in an MIUS system at the same time it is demanded by the HVAC system. Storing thermal energy until it is needed ensures maximum energy conservation. Thermal energy can be stored in materials using either the latent or sensible heat of the material and recovered at a later time. Thermal energy can be stored either above or below the ambient temperature.

The most commonly used material for heat storage is water because it is plentiful and inexpensive. The temperature range over which it is practical to use the sensible heat of water for energy storage ranges from almost freezing to boiling. Of course, the trade-off of insulation, capacity, and surrounding conditions must be considered in any analysis of storage systems.

Several other mediums are prime candidates and in some cases currently in use for energy storage. Phase-change materials, which have advantages over water, have been given considerable attention recently. Salt hydrates are known to have phase-change temperatures convenient for heating uses. In addition to pure salt hydrates, eutectic salt hydrates have been made that have phase-change temperatures in the range of air-conditioning evaporator temperatures, which makes them useable for low-temperature storage.

An insulated tank with distribution pumps and pipes can be used to store energy. If the storage and distribution fluids are not the same, a heat exchanger is necessary. If a tank can be located in the ground, insulation may not be required. Although the advantages of energy storage systems are obvious, costs may be prohibitively high. The size of the storage container is often dictated by the available area; as a result, higher capacity storage media are continually under investigation. In MIUS uses for high-density areas, energy storage reservoirs may not be feasible.

Energy storage systems are in limited use in present building systems. These systems store hot water in the winter and chilled water in the summer, often using the same tank. Eutectic salt storage systems are being investigated by the Army Mobility Equipment Research and Development Center in Arlington, Virginia. The salts store energy during low cooling demand periods and release the energy during periods of peak demand. Eutectic storage systems are manufactured commercially by Artech Corporation of Falls Church, Virginia. In an integrated utility system, energy storage is desirable, but extensive trade studies are necessary to determine effectiveness.

## HEAT REJECTION

Heat rejection is vital to a utility system. Three general categories of heat-rejection devices that were investigated for MIUS use were cooling towers, spray ponds, and radiators.

### Cooling Tower

The most common heat-rejection system used today is the cooling tower. A cooling tower is a device that cools water by evaporation. This is done by spraying or flowing the water over a system of slats that break the water into droplets. Cooling towers are categorized as atmospheric towers, mechanical-draft towers, or hyperbolic towers. An atmospheric tower is a spray-filled tower with louvered walls and an elevated spray system. Some natural wind is needed to carry hot vapors away. The cooling ability of an atmospheric tower is limited to 10 K (15° F) above the ambient wet-bulb temperature, depending on the velocity of the wind. Water-cooling systems in which temperature control requirements are stringent do not readily adapt to wind-dependent cooling.

The most prevalent cooling tower currently in use is the mechanical-draft tower. This tower is equipped with fans to provide constant airflow. The addition of the fan makes it possible to design more compact towers with better cooling control. Some recirculation of exhaust vapors can occur under certain natural wind velocities and directions, and this detracts from performance in an unpredictable fashion. These towers are available in almost any size from small package units to large-capacity, field-erected, multicelled industrial installations. Package units typically range from 10 to 1000 tons. (An evaporative ton is 15 000 Btu/hr.) The costs range from \$65/ton to \$14/ton, respectively, free on board from the factory. Commercial field-erected towers range from 50 to 1500 tons in single-cell units. There is no limit to the total size of industrial towers available. Many are in the 10 000- to 35 000-ton capacity range and can be installed for \$11/ton. Typical annual operating costs for commercial towers in the 100- to 1200-ton range total approximately \$50/ton to \$30/ton. Total annual operating costs are given in reference 6. The hypergolic or natural-draft (chimney-type) tower depends on the difference in density of the heated air and outdoor air to produce continuing flow through the tower. Variations in the ambient temperature conditions affect performance.

#### Spray Pond

Spray ponds are about the simplest and therefore least expensive evaporative cooling devices used for industrial water cooling. The pond acts as a collecting basin. If much wind is present, significant amounts of water are lost because of drift, which may be troublesome.

#### Forced-Air Radiators

The use of forced-air radiators for MIUS-type requirements has been limited. Forced-air radiators are being used supplementally with cooling towers on the Operation Breakthrough, Jersey City, site. When the radiators are used without the towers, they often prove to be inadequate on hot days because the lowest temperature to which a radiator could cool the water would be above that of the ambient air, which might be significantly higher than the maximum temperature of 303 K (85° F) for condenser water for the absorption chiller. This means that, on hot days, cooler makeup water must be mixed with the radiator outlet water.

## Water Treatment

In cooling towers and spray ponds, the evaporation of the water results in an increased concentration of dissolved solids. This buildup would eventually affect the cooling performance. The level of concentration can be sensed by the water-conductivity measurement, and the cooling tower is automatically blown down to maintain the desired level of dissolved solids. Algae growth also affects performance of evaporative cooling devices, but this can be controlled by the addition of sulphuric acid to maintain a pH level between 6.5 and 7. The closed system radiator does not have the water treatment and makeup requirements of cooling towers and spray ponds, but initial treatment is necessary to prevent scaling and corrosion.

## Heat-Rejection Conclusions

It appears that heat-rejection for MIUS uses will be accomplished by evaporative cooling to take advantage of the tower temperature of heat rejection. This equipment is in common use; therefore, performance data and equipment are price competitive and easily available. There are many disadvantages in using cooling towers. Evaporation is the principal mode of heat rejection. Under certain meteorological conditions, this vapor will condense on leaving the tower, producing a haze or fog that can interfere with traffic. The typical cooling tower loses approximately 0.1 percent of the water being circulated in it by drift, and this drift carries off dissolved solids. These dissolved salts are hazardous to adjacent vegetation. The highly aerated water combined with dissolved solids is highly corrosive. The dissolved salts in the cooling tower and the chemicals added to the coolant water to suppress algae may present a liquid-waste-disposal problem. The extensive use of baffles and the necessity for powerful fans to aerate cooling water present noise problems that must be carefully controlled. The use of radiators will have to be considered in further depth to determine their applicability to the MIUS concepts. The basic simplicity and simpler water-treatment requirements of radiators are desirable traits.

## DISTRIBUTION SYSTEMS

The purpose of air distribution in warm air heating, ventilating, and air-conditioning systems is to create the proper combination of temperature, humidity, and air motion

in the conditioned air space. To obtain comfort conditions within this space, standard limits have been established for the acceptable effective temperature. This term comprises air temperature, air motion, relative humidity, and the physiological effect of these conditions on the human body. Any variation of one of these elements from accepted standards may result in discomfort to the occupants. The distribution systems discussed in this section include basic air-conditioning systems and techniques for distributing heating and cooling fluid media as well as the ducting technique for air distribution.

### Air-Handling Systems

Air systems can generally be classified as single duct and dual duct with variations of these. Dual-duct systems consist primarily of a hot air duct and a cold air duct arranged to serve mixing boxes throughout the building from the central conditioning systems within the equipment room. The main advantage of the dual-duct system is that the individual spaces served may be temperature controlled to the requirements of the occupants. In addition to requiring more ductwork, energy is wasted in the dual-duct system because both hot and cold air must be provided. Single-duct systems have several variations, but the basic system accomplishes preliminary heating or cooling at the equipment room, and the final temperature is controlled at the distribution outlet.

Both single- and dual-duct systems can transport high-pressure air and consequently have smaller cross-sectional areas, which saves space and ducting material. The high-pressure air is released through jets into a plenum chamber where it is combined with the room air and then returned to the room as conditioned air.

Insulations in duct systems can be either external or internal. External insulations provide thermal insulation, and the interior insulations provide sound as well as thermal insulation. The interior insulation must be designed to withstand the airflow.

### Water Systems

Heat transfer in HVAC systems is accomplished with two-pipe, three-pipe, and four-pipe arrangements that have distinguishable advantages and disadvantages. The two-pipe system, the most economical in initial investment, carries either warm or cool water, depending on the outside

temperature. The two-pipe system cannot provide extra cooling on the sunny side of a building when the general air temperature is adjusted for heating. If the temperature on the shady side of the building is too low, nothing can be done to increase it while the system is operating in the cooling mode. The three-pipe system has a warm-water pipe, a chilled-water pipe, and a common return. With this system, individual air unit mixing boxes can raise or lower temperature as the occupants desire. The four-pipe system accomplishes the same effect but has separate warm- and chilled-water returns. The three-pipe system does not conserve the energy required to heat and cool the initial water supplies.

### Heating/Cooling Modulation Techniques

There are four techniques used for modulating the effective heating and cooling of the air space.

1. Waterflow through the fan coil unit is constant, and fan speed is modulated. The constant transferring of some thermal energy is a disadvantage of this system.

2. Fan speed is constant, and the waterflow through the fan coil unit is modulated.

3. Fan speed and waterflow through the fan coil unit are both modulated.

4. Fan speed is constant. The ambient temperature is measured, and controls are provided to mix the hot water with ambient temperature water and feed the resulting mixture through the fan coil unit.

Two techniques are used for controlling the airflow rate through the distribution system to the individual air space. In one method, individual dwelling units are fed in series so that the flow to the first dwelling unit should be the same as the flow to the last dwelling unit. Flow is controlled by using different pipe sizes between the main distribution line and the local unit in the dwelling. This system is engineered in the initial design stages, which does not provide for making later adjustments. The number of pipe sizes used is an additional complexity factor.

Control valves are also used to adjust the airflow from the main distribution line to the heating or cooling units in the dwelling unit. These valves usually are simple flow constrictors that can be manually adjusted to make final system flow adjustments.

## Distribution Systems Conclusions

All the distribution system techniques discussed are being used in state-of-the-art equipment. The four-pipe system with control valves and constant-speed fan coils is the prime MIUS candidate for distribution. The factors that support this system as the prime candidate are as follows:

1. The four-pipe system provides for simultaneous heating and cooling in a building complex, thus providing a more flexible heating/cooling system.

2. The use of manual air control valves provides the capability for making airflow adjustments after system completion.

3. Systems that modulate waterflow are readily available and provide more flexibility of operation than air-flow modulating systems.

## VENTILATION REQUIREMENTS AND TECHNIQUES

Ventilation involves replacing contaminated air with fresh air. Air-conditioning systems are designed to control the temperature, humidity, and air cleanliness within a given space. The primary reason for ventilation is to sustain personal comfort and to maintain the health of the occupants. A desired objective of ventilation is to provide an odor-free environment. The important considerations that must be taken into account to provide an odor-free environment are (1) activity of occupants, such as cooking, smoking, deskwork, manual labor, et cetera, (2) air space allowed per person, (3) odor removal capacity of the air-conditioning processes, (4) temperature and relative humidity of the room, (5) external pollution conditions, and (6) hygienic habits of occupants (young people, old people, dogs, cats, etc.). Some design constraints relating to odor-intensity production compared to ventilation flow rates are as follows:

1. Outdoor air requirements can be determined by gaging the odor produced.

2. Individuals emit varying amounts of odor.

3. Recirculated air can be rendered relatively odor free by washing, humidifying, cooling, and dehumidifying.



4. The odor varies inversely with the logarithm of the flow rate of outdoor air supplies and directly with the logarithm of air space allowed per person.

5. A healthy, clean person who is freshly bathed requires 0.42 to 0.51 m<sup>3</sup>/min (15 to 18 ft<sup>3</sup>/min of air) to dilute body odors.

6. Children require slightly higher ventilation rates than adults because of their higher activity level.

7. Carbon dioxide concentration is an unreliable index of adequate ventilation because its concentration is not proportional to the odor intensity.

Additional odors and combustion products are added to an air space through cooking, smoking, and untreated outside air. The established industrial standard for residential flow rate is 0.71 m<sup>3</sup>/min (25 ft<sup>3</sup>/min) when the air space is 2.83 cubic meters (100 cubic feet) per person.

Ventilation requirements are satisfied by several methods.

1. Infiltration results from air leaking into and out of a dwelling unit around windows and doors, et cetera.

2. Natural ventilation is the movement of air by the wind and air convection currents caused by temperature differences between the interior and exterior of a building.

3. Induced ventilation is the transport of unconditioned air by fans between the occupied space and the environment.

4. Forced air is the movement of air in ductwork associated with air-conditioned heating and cooling systems. The ventilation mode of operation of these air-handling units is provided by a damper to regulate the supply of outdoor air being mixed with the circulated conditioned air. The equipment used ranges from packaged air conditioners to large custom-designed units integrated into a huge central system serving an entire complex of buildings. In the case of a packaged unit, the fan may be included as an integral part of the equipment. In large custom-designed plants, a centralized fan system is often used to distribute conditioned air. Separate supply, exhaust, and recirculating fans may be used. Forced-air flow is controlled by one of two basic methods: (1) constant fan speed where regulation is achieved by air-duct flow control or (2) variable fan speed where the air pumping power is

adjusted. Constant-speed methods are generally less expensive and less complicated than variable-speed drives but also tend to be less efficient. Factors affecting the selection of unit ventilators are air capacity, air change rate requirements, heating and cooling capacity, and flow control.

Noise control is an important aspect of duct design. Research in noise control has been extensive during the last decade and is in a constant state of revision. Technical papers consulted in the preparation of this report cover a wide range of topics: sound attenuation ducts; noise from fans, grills, and diffusers; schemes for rating noise output; machine design; vibration mountings for and isolation of compressors and fans; ordinances regulating air-conditioner noise; chiller noise and its impact on building design; instrumentation for sound power measurements; and standards for the measurement of noise and vibration. The most extensive coverage available is given in reference 7.

## HUMIDITY CONTROL

During the heating season, the relative humidity often decreases to uncomfortable levels so that the moisture content of the building air must be increased to maintain a humidity level within the comfort zone. In contrast, the cooling season often requires the removal of moisture. Lowering the temperature of air can raise the relative humidity to uncomfortable levels if the air is not dehumidified.

### Humidification

A qualitative comparison of common types of residential humidifiers can be obtained from the National Warm Air, Heating, and Air Conditioning Association. The general principles of operating the residential units are as follows:

1. The basic pan is shallow but has a fairly large area for evaporation and can be installed within the air-duct plenum. A float valve control device connected to the household water supply maintains a constant water level in the pan. The electrically heated pan is similar to the basic pan except that an electric heater is used to increase the rate of evaporation. Pans with wicking-type plates are arranged so that several vertical, water-absorbent plates are added to the pan to increase the wet surface area.

2. In using wetted elements, air is circulated through or over an open-textured, wet media. The evaporation surface may be a fixed pad, which is wetted by sprays or by water flowing through by gravity from a header at the top. The pad may also be a paddle wheel, drum, or belt rotating through a water reservoir. Airflow through such units is usually accomplished in one of three ways.

a. In fan-type units, a small fan or blower is used to draw air from the plenum through the wet pad and back to the plenum.

b. In bypass units, fans are not used, but the unit is mounted on the supply plenum with an air connection to the return plenum. The difference in static pressure created by the main blower circulates air through the unit.

c. Duct-mounted units are designed for installation within the plenum or ductwork with a drum-type element rotated by the air movement within the duct or by a small electric motor.

3. In using atomizing-type humidifiers, small droplets of water are introduced directly into the airstream by a spinning disk or cone, which breaks the water into fine mist; by sprays, which rely on water pressure to create fine droplets; or by a rotating disk, which slings water droplets into the airstream from a water reservoir. Water particles may evaporate in the airstream, if fine enough, or may be deposited on the interior ductwork and subsequently evaporate.

### Dehumidification

Cooling air below its dewpoint is the usual method of dehumidification and normally occurs as part of the air-conditioning process. This dehumidification is adequate for the majority of applications. There are cases, however, where there are very high densities of people in buildings. For these conditions, additional dehumidification above that provided by the air-cooling system may be required. This dehumidification can be accomplished by compression followed by cooling and expansion and liquid and solid sorption or a combination of these systems.

Compression followed by cooling and expansion of the gas to be dehumidified will reduce the absolute moisture content of the air but will generally produce a saturated condition in the final low-pressure state. This method is not economical in most cases. Dehumidification may be accomplished by cooling or sorption, or both, depending on

the requirements of the dewpoint at the point of use (refs. 8 and 9).

In liquid sorption dehumidification systems, gas is passed through sprays of a liquid sorbent such as lithium chloride or a glycol solution. The sorbent that removes moisture from the gas stream is regenerated, and moisture is emitted to an outdoor airstream when the solution is heated. A partial bleedoff of the solution is used to continuously reconcentrate the sorbent.

In solid sorption, granular beds or fixed desiccant structures are used in automatic machines in which the gas stream is passed through a granular desiccant. Many commercially available desiccants may be used depending on the character of the gas to be dried, inlet temperature, moisture levels, and required final dewpoint. Outdoor air is passed through beds or layers of the sorbent, which absorbs moisture from the gas stream. After becoming saturated with moisture, the desiccant needs periodic reactivation.

When very warm air of high moisture content is to be treated to produce cool, very dry air, dehumidification by the two-stage process of chilling by compression refrigeration followed by solid sorption may prove to be more economical, in terms of space and power, than using either of these methods. A single solid sorption system can usually be justified economically where low utility rates permit inexpensive reactivation of the sorbent. In the reheat air-conditioning cycle, the humidity control is affected by the incoming cool air to a dewpoint corresponding to the final desired air state. The air is then reheated to the desired temperature.

#### Humidity Control Conclusions

The spray-atomizing system is one of the most promising humidity control systems because of its low cost, simple installation, low maintenance, and low power requirements. The degree of dehumidification required varies greatly with different applications and is one of the prime considerations influencing the choice of the method to be used.

#### AIR FILTRATION

There are a multitude of filtration devices commercially available that are designed to perform a large

variety of tasks. This discussion is directed to applications of filters in the air-handling equipment for the MIUS.

In selecting a filtration system, the primary considerations are (1) arresting efficiency, (2) quantity of contaminant held before airflow resistance is detrimental, (3) initial, replacement, and operating costs, (4) maintenance required, (5) fire resistance, (6) dimensions of the filter device, and (7) pollen and dust loads in the ambient air. Generally, the higher the cleaning efficiency, the greater the resistance to airflow and the higher the initial and operating costs. It is unreasonable to select higher efficiency filtration systems than the situation demands.

There are four common types of air filtration systems used in residential/industrial applications that might be incorporated into MIUS. The systems are (1) fibrous media unit filters, (2) renewable media filters, (3) electronic air cleaners, and (4) sprayed media air cleaners.

Fibrous media unit filters operate by accumulating dust on the media surface. These filters, which are usually replaceable, are changed when the accumulated dust significantly restricts airflow. These filters can be classified as viscous (coated with an adhesive material such as oil) or dry.

Renewable media filters are classified as moving-curtain viscous impingement filters and moving-curtain dry media filters. Both types can be motor or manually driven rolls that are wound on a takeup spool after use and then discarded.

Electronic air cleaners use electrostatic precipitation to collect particulate matter. The term electronic air cleaner distinguishes this cleaner from electrostatic precipitation devices used in industry. This system is suitable only for cleaning ventilating air. Two types are produced for commercial use.

Ionizing electronic air cleaners generate positive ions that adhere to dust particles carried in the airstream. These dust particles pass into a system of electrostatically charged plates on which they are deposited. These air cleaners are low-pressure drop devices for removing dust and smoke particles. Cleaning is accomplished by washing removable plates in hot water or placing rinse nozzles in the system. A disadvantage of this system is that charged particles not picked up by the plates tend to be attracted to walls and other static-charged material in the living

space, necessitating more frequent cleaning; arcing can produce ozone concentrations.

Charged-media electronic air cleaners that consist of a dielectric filtering medium arranged in plates as in a typical filter combine features of dry filters and electronic air cleaners. No ionization is used. The filter media is in contact with an alternately charged and grounded gridwork. The dielectric properties of the media are impaired when the relative humidity exceeds 70 percent.

Two processes take place in sprayed media air cleaners. The spray that passes through air alone compares to typical low-efficiency dry-media filters. The cleaning process is greatly enhanced by passing the air through a filter of glass fiber or other capillary medium while that medium is being sprayed. The air exiting such a cleaner system is saturated with water (i.e., at the dewpoint). This dewpoint can be controlled by the temperature of the spray water.

The gaseous pollution of the air is a primary concern. No media filter or electrostatic precipitator can eliminate this pollution from the air; however, water is an excellent solvent for gases and is a cheap and effective means for removing toxic gases and odors.

Sprayed media filters are relatively new, but simplicity of design should allow for easy incorporation into MIUS. These filters offer a combination of advantages not available in any other single cleaning method.

1. At least some of the gaseous pollution is removed from the air.
2. For the quality of filtering, the air resistance is low.
3. With a good flushing spray, there is no dirt buildup on the media.
4. If the spray nozzles are not allowed to deteriorate, the media replacement is nearly eliminated, resulting in low maintenance costs.

#### ODOR CONTROL

To make living spaces more habitable, some method of odor control must be adapted because undesirable odors become more intense as living densities increase. The

understanding and control of odor is at this time as much an art as a science. Many odor control methods are being used for a variety of applications. Odors can be removed or controlled by ventilation, air washing or scrubbing, absorption, chemical reaction, combustion, counteraction, and masking (ref. 10).

In earlier years, odor control in housing was accomplished almost accidentally by infiltration. With modern construction, it has become increasingly necessary to use positive control methods. This control is currently most commonly effected by forced ventilation; the rate being so established that the makeup air dilutes the odor to an acceptable level. With the increasing pollution of outdoor (makeup) air and the concentration of multifamily dwelling units, more positive control may become necessary.

A combination of the odor control techniques currently being used may be applicable to MIUS. In addition to the normal ventilation of air, air washing by a sprayed-media filtration system seems to be desirable.

#### ELECTRICAL AND MECHANICAL CONTROLS AND EQUIPMENT

A variety of heating, cooling, and ventilation control devices will be necessary for use in MIUS because successful operation (in respect to energy conservation) is dependent on the coordination of sensing and control devices for each component. A comprehensive description of pertinent automatic controls is given in reference 11. Many excerpts from this reference have been used to categorize the equipment for this assessment.

Control mechanisms are divided into six groups according to the source of energy.

1. In the self-contained system, power of the measured system is used to effect the correction action.

2. In the pneumatic system, compressed air is supplied to the controller to regulate the pressure supplied to the controlled device.

3. In the hydraulic system, a suitable liquid is used under pressure to operate control devices where larger operating forces are required.

4. In the electric system, either low or line voltage is used directly or through relays. The energy supplied to the controlled device is regulated by the controller.

5. The electronic system is similar to an electric system except that the electronic amplifier replaces the relay.

6. Various combinations of the aforementioned systems are used for specific applications.

The automatic controls for heating, ventilating, and air conditioning systems may be subdivided into controllers, controlled devices, and auxiliary control equipment. These categories are further explained in the following listing.

## 1. Controllers

### a. Thermostats

- (1) Room type designed for wall mounting
- (2) Insertion type designed for wall-duct mounting with sensing element in duct
- (3) Immersion type for pipes and tanks
- (4) Remote-bulb type where sensing element is distant from thermostat
- (5) Day/night types for sensing and changing daily operations
- (6) Heating/cooling type for sensing and changing seasonal operations
- (7) Multistage thermostats for sensing and operating sequential steps
- (8) Submaster types controlled by master thermostats for changeable functions

### b. Humistats (room or insertion type)

- (1) Wet-bulb thermostats
- (2) Dewpoint thermostats

c. Pressure or static-pressure controllers (mounted remotely or in the vicinity of the measured pressure)

## 2. Controlled devices

### a. Automatic valves



- (1) Single seated
- (2) Pilot piston
- (3) Double seated or balanced
- (4) Three way mixing
- (5) Three way diverting
- (6) Butterfly
- b. Valve operators
  - (1) Solenoids
  - (2) Electric
  - (3) Pneumatic
- c. Automatic dampers
  - (1) Single blade
  - (2) Multiblade or louver
  - (3) Mixing

3. Auxiliary control equipment includes such apparatus as switches and relays of various kinds, clocks or timers, thermometers, gages, pilot lights, transformers, potentiometers, recorders, et cetera, to perform special functions.

#### NASA RESEARCH AND DEVELOPMENT TECHNOLOGY APPLICABLE TO THE MIUS PROJECT

The following sections briefly highlight some aspects of NASA research and development technology.

##### Thermal Control

Advanced thermal control technology can be applied to utility systems by using heat pipes, improved insulations, and thermal coatings. Brief descriptions of processes, principles, operational characteristics, and NASA use of thermal control technology are included in table II.

The basic heat pipe is a closed container that has been evacuated of all noncondensable gases, contains a capillary wick structure, and has a small amount of vaporizable fluid. A boiling/condensing cycle is used in the heat pipe, and the capillary wick transfers the working fluid from the condenser to the evaporator (fig. 5). The heat pipe can be used as a variable temperature control of a variable conductance device by the introduction of noncondensable gases into the heat pipe and by controlling the pressure of this gas by active or passive means. Further details of variable heat pipes are discussed in reference 12.

The vapor pressure drop between the evaporator and the condenser is very small; therefore, the boiling/condensing cycle is essentially an isothermal process. The use of heat pipes to transmit and distribute heat is in the early stages of application in utility systems. Heat pipes have been used for transferring heat between inlet and outlet ventilation ducts and for recovering heat from power generation and equipment or furnace exhaust for use in preheating, et cetera.

Because heat pipes have no moving parts, they can be used as heat-transfer devices that have potential applications within the home. Heat-pipe technology has progressed significantly within the last few years. Governmental organizations and private industry have sponsored analytical and experimental programs for aerospace use. Notable contributors to the recent heat-pipe technology include Los Alamos Scientific Laboratory, NASA Goddard Space Flight Center (GSFC), NASA Lewis Research Laboratory, and NASA Ames Research Center (ARC). Heat-pipes have been flown successfully on unmanned spacecraft (e.g., the application technology satellite). A variable-conductance, constant-temperature heat pipe is being studied by the ARC. A contract was recently awarded by the Lyndon B. Johnson Space Center (JSC) for design, fabrication, and analysis of two 15-meter (50-foot) circumferential heat-pipe systems. The purpose of this work is to initiate the use of the heat-pipe technology for large systems.

High-performance insulation materials were developed for use on the current generation of manned and unmanned spacecraft. This reservoir of design information and hardware provides a sound baseline for developing improved insulation systems for housing and urban development application (e.g., water tanks, pressure vessels, fluid lines, air ducts, structure insulation, etc.).

During the past decade, significant advances have been made in the development of thermal control coatings to be used for a variety of spacecraft requirements. These

coatings may be applicable for controlling terrestrial radiation heat transfer. Coatings could be used on the exterior surfaces of a house and on radiative surfaces to improve their performance. Most of the current thermal control coating research and material development is being conducted at the Marshall Space Flight Center (MSFC). This effort is devoted primarily to the development of space radiator thermal control surface properties with long-time stability when exposed to solar radiation. Additional work is being done at the Jet Propulsion Laboratory, JSC, LRC, and GSFC. Current thermal coating technology is directed toward the development of coatings that can be cleaned readily without degrading their thermal properties.

### Thermal Energy Dissipation

Brief descriptions of processes, principles, operational characteristics, and NASA use of thermal energy dissipation technology are given in table III. In addition, space radiators have used conventional refrigerant fluids (e.g., ethylene glycol, FC-75, water, Coolanol, and Freon 21). Therefore, the radiator technology that NASA has developed during the past decade is directly applicable to radiant heating and cooling techniques that could be used in homes and commercial buildings. Space radiators that are capable of dissipating 2 kilowatts of thermal energy have been used on Apollo spacecraft. Current NASA technology is directed toward the development of modular radiator systems that can accommodate a wide range of heat loads and a variety of vehicle configurations. In addition, development of radiator heat-rejection systems capable of dissipating approximately 1000 kilowatts of thermal energy is being pursued. These investigations will provide information on various heat-rejection design concepts such as fixed and deployable radiators (sleeve type, folding, or louvered type, etc.), condensing and noncondensing fluids, various fin geometries and fin-type system configurations, and the design and operational requirements associated with each concept. Compatibility of high-temperature structural materials and coolant fluids with long lifetime capability is a paramount problem that is being studied. Black-body radiators (solar thermal absorbers) that have been studied and tested by NASA may have applicability for use as terrestrial solar heat collectors. Under recent MSFC contracts, the use of solid/solid phase-change materials for space thermal control was investigated. Specific new materials that can be used as phase-change thermal control materials were defined, selected, and evaluated. They may have direct application in storing energy to minimize peak power requirements.

Throughout the space program, conventional fluids for heat-transport thermal-control circuits have been used in space vehicles. This reservoir of information on fluids and plumbing techniques provides a sound baseline for the development of fluid-circuit design for housing and urban development use (e.g., improved valves, integrated fluid-circuit design, etc.).

Refrigeration techniques including thermoelectricity, vapor compression, absorption, and adsorption have been and are being studied and tested by NASA. Many companies are currently investigating the use of thermal-electric devices. This work involves the entire spectrum of activity from small-scale research to the development and marketing of commercial generators and coolers. Several companies have developed thermal-electric devices for such applications as cooling devices for use as low-temperature spot coolers for electronic components and refrigerators. The MSFC has built a small cooling system for laboratory evaluation.

#### Environmental Control

Brief descriptions of processes, principles, operational characteristics, and NASA use of environmental control technology are given in table IV. As in a room on Earth, ventilation is required in a spacecraft. Independently located fans and air returning from air-processing equipment provide ventilation in spacecraft. Test programs have been conducted at JSC to develop optimum air-circulation-analysis techniques that will provide adequate flow distribution throughout the room (to eliminate dead spaces and drafts) with minimum fan circulation requirements, which will result in minimum power usage. Development of analytical techniques for the design and optimization of low-noise, high-efficiency fans have been conducted at JSC. In addition, noise abaters, which can probably be used in household designs, are used in circulation ducts to reduce the noise levels.

Temperature and humidity control are normally regulated by fans and heat exchangers, not only in spacecraft but also in households. Analytical techniques have been developed at JSC for the design and optimization of heat exchangers. In addition to condensing heat exchangers, desiccants are being investigated as a humidity control technique for the Space Shuttle Program. Desiccants have been used for many years by NASA as part of the carbon dioxide collection techniques. Desiccants absorb water when cooled and release water when heated; thus, this technique of humidity control may be useful in households because of the availability of hot and cold water. Condensed water in a dehumidifier must be

collected and disposed of on Earth and in space. Several water separators have been developed, tested, and flown by NASA, including devices using hydrophobic/hydrophilic surfaces, rotary or vortex generators, and external wick separators. If condensed water is recycled, any of these techniques can be used.

The processes for controlling gaseous contaminants in air are generally divided into sorption methods, which remove certain constituents, and oxidation methods, which convert certain constituents into innocuous materials (table V). To confirm performance of either of these processes, measurement and detection methods are available for monitoring trace gases. Some of the pertinent NASA experience associated with these activities is described in the following discussion.

The major method of odor removal is by sorption. The active materials usually used in this process include activated charcoal, silica gel, aluminum oxide, or potassium permanganate. Several programs on charcoal development ranging from basic materials screening evaluations to methods for reusing spent charcoal have been supported by NASA. These activities have produced methods for vacuum and thermal regenerations of charcoal. Currently, NASA is involved in a joint program with the Water Quality Office of the Environmental Protection Agency to evaluate experimentally an electrochemical method of charcoal regeneration. If successful, this research is expected to produce a charcoal regeneration method that will be useful for rapid regeneration of large amounts of material. For trace contaminants that are not readily removed by charcoal, chemisorbent materials such as copper sulfate or potassium permanganate are useful. The NASA investigations of chemisorbent materials include both laboratory material evaluations and design and testing of prototype sorber units.

The NASA has conducted programs in catalyst selection, preparation, fabrication, and testing of the area of catalytic oxidation of trace contaminants, which include prototype units. Testing has involved small-scale laboratory evaluation and operation of units in manned chamber runs. The results of these activities have established a technical base in catalytic oxidation that may be useful in ventilation airflow and cleanup of flue gases from incineration or heating units.

The NASA development in atmospheric-trace-contaminants monitoring equipment has produced prototype and flight hardware. A carbon dioxide sensor, flown during the Apollo Program, has potential as a household fire-warning device.

Automated monitoring prototype instrumentation using mass spectrometer and gas chromatographic techniques has been developed for a wide spectrum of trace contaminant gases. Such measurement would be useful in determining proper operation of odor control equipment or when changeout or regeneration of sorbents should be performed.

The NASA has conducted numerous manned integrated environmental thermal control and life-support system tests in vacuum chambers for periods as long as 90 days. These tests have provided NASA with insight in the area of acceptability and maintainability of water reclamation equipment that could be used to reduce household water requirements.

#### CONCLUDING REMARKS

Although numerous methods are available for producing air conditioning, this survey indicates that the types of air-conditioning chillers in common use today are highly efficient devices, and both single-stage absorption and compression chillers will probably be used in a modular integrated utility system. There does not appear to be any requirement to develop new devices for heating, ventilation, and air-conditioning auxiliaries in the modular integrated utility system program. Some previous NASA experience in thermal control may be applied in this program.

Lyndon B. Johnson Space Center  
National Aeronautics and Space Administration  
Houston, Texas, December 21, 1973  
386-01-00-00-72

## REFERENCES

1. Anon.: ASHRAE Handbook of Fundamentals. Sec. I, ch. 6, Sound Control Fundamentals. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1972.
2. Anon.: Systems Volume. Ch. 10, Steam Heating Systems. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1970.
3. Anon.: Systems Volume. Ch. 33, Sound and Vibration Control. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1970.
4. Anon.: Residential Energy Consumption, Multi-Family Housing Data Acquisition. Rep. no. HUD-HAI-3, Hittman Associates, Inc. (Columbia, Maryland), Oct. 1972.
5. Anon.: Residential Energy Consumption, Multi-Family Housing Data Acquisition. Residential Energy Consumption (Phase I Report). Rep. no. HUD-HAI-1, Hittman Associates, Inc. (Columbia, Maryland), Mar. 1972.
6. Malkin, S. I.: Cooling Tower Economics. Plant Eng., vol. 25, Nov. 11, 1971, pp. 103-105.
7. Anon.: Systems Volume. Sec. IV, ch. 35, Sound and Vibration Control. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1973.
8. Anon.: Equipment Volume. Sec. I, ch. 6, Air-Cooling and Dehumidifying Coils. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1972.
9. Anon.: Equipment Volume. Sec. I, ch. 7, Sorption Dehumidification and Pressure Drying Equipment. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1972.
10. Anon.: Systems Volume. Ch. 31, Odor Control. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1970.
11. Anon.: Systems Volume. Ch. 32, Automatic Control. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1970.

12. Marcus, B. D.: Theory and Design of Variable Conductance Heat Pipes. NASA CR-2018, 1972.

#### BIBLIOGRAPHY

- Althouse, Andrew D.; Turnquist, Carl H.; and Bracciano, Alfred F., eds.: Refrigeration and Air Conditioning. Goodheart-Willcox Co., Inc. (Homewood, Illinois), 1968.
- Archie, John L.: Absorption Refrigeration Systems. ASHRAE Journal, Sept. 1971, pp. 41-45.
- Barrangon, Maurice: The Gas Engines - On-Site Prime Movers. ASHRAE Journal, Feb. 1970, pp. 50-53.
- Burnett, Thomas E.: A Practical Approach to Air Cleaning. ASHRAE Journal, Apr. 1971, pp. 48-50.
- Evans, Benjamin H.: HVAC Evolution as It Affects the Design Engineer. ASHRAE Journal, Nov. 1971, pp. 56-58.
- Peach, Norman: All Plant Energy from a Single Source; A Special Report on All-Electricity and All-Fuel Systems. Power, vol. 112, no. 12, Dec. 1968, pp. S-1 to S-24.
- Segerstrom, Stewart: Heat Pumps Today. ASHRAE Journal, July 1971, pp. 63-65.
- Whitlow, E. P.: Trends of Efficiencies in Absorption Machines. ASHRAE Journal, Dec. 1966, pp. 44-48.



## APPENDIX

### ACKNOWLEDGMENTS

Leon Kazan and Robert Seltizer  
Utilities Engineering Associates  
Whitemarsh Building  
15 Ridge Pike  
Conshohocken, Pennsylvania 19428  
215-825-3850

Jack Smith, Robert Smith, and John Dixon  
Smith and Boucher, Inc.  
Two Crown Center  
Kansas City, Missouri 64108  
816-421-3715

Albert H. Eatwell  
Truog Nichols, Inc.  
P.O. Box 2093  
Shawnee Mission, Kansas 66201  
913-888-6401

James Yoke  
MW Inc.  
700 North High School Road  
Indianapolis, Indiana 46224  
317-243-8321

R. D. (Dean) Wear  
J. A. Peterson Co.  
Total Energy Systems  
Kansas City, Kansas  
913-362-7691

Weldon W. Henderson  
Jochen and Henderson, Inc.  
2400 West Loop South  
Suite 100  
Houston, Texas 77027  
713-623-2000

Douglas G. Harvey  
Hittman Associates, Inc.  
9190 Red Branch Road  
Columbia, Maryland 21043  
301-730-7800

H. Harry Phipps  
Energy Systems Consultants  
6803 Sea Gull Drive South  
St. Petersburg, Florida 33707  
813-345-2701

Morey Gamze  
Gamze, Korobkin, and Calloger, Inc.  
Chicago, Illinois  
312-641-5988

James King, Deputy Director  
Division of Professional Service  
Office of Construction Management  
Public Building Service  
General Service Information  
Washington, D.C. 20546  
202-343-5151

Dr. Steve Freedman  
University of Pennsylvania  
National Center for Energy Management & Power  
113 Towne Building  
Philadelphia, Pennsylvania 19104  
215-594-7181

Prof. C. A. Morrison  
Mechanical Engineering Department  
University of Florida  
Gainesville, Florida 32601  
904-791-2011

Elmer Havens  
Assistant Director for Research  
Office of Programs & Resources  
National Science Foundation  
Washington, D.C. 20546  
202-632-4290

Curtis Pederson  
College of Engineering  
University of Illinois  
Urbana, Illinois 61801  
217-333-1000

David Houston, Editor  
ASHRAE  
United Engineering Center  
345 East 47th Street  
New York, New York 10017  
212-460-0100

Bill Megley, Consulting Engineer  
Megatherm Corporation  
Boston, Massachusetts  
617-888-1862

M. Wayne Kitchen  
Manufacturing Engineering Department  
Garrier-Houston Company  
7007 Katy Road  
Houston, Texas 77024  
713-869-3511

Charles W. Kaufman, Manager  
District Sales Department  
Carrier Air Conditioning Company  
7007 Katy Road  
P.O. Box 19308  
Houston, Texas 77024  
713-869-3511

James A. Beach  
Director of Utilization  
United Gas  
P.O. Box 2628  
Houston, Texas  
713-228-5111

Dale S. Cooper  
Dale S. Cooper & Associates  
Houston, Texas  
713-562-1585

Kenny Poff and Jim Eamil  
Sales Department  
Waukesha-Pearce Industries, Inc.  
Box 35068  
Houston, Texas  
713-723-1050

A. J. Pennington  
Decision Sciences Corporation  
Benjamin Fox Pavilion  
Jenkinstown, Pennsylvania 19046  
215-707-1970

Paul R. Achenbach, Chief  
Sensory Environment Branch  
Building Research Division  
National Bureau of Standards  
Gaithersburg, Maryland 20760  
301-921-3637

Frank Powell  
Thermal Energy Section  
Building Research Division  
National Bureau of Standards  
Gaithersburg, Maryland 20760  
303-921-3501

Clinton Phillips  
Environmental Engineering Section  
Building Research Division  
National Bureau of Standards  
Gaithersburg, Maryland 20760

J. Miller  
Oak Ridge National Laboratory  
Oak Ridge, Tennessee

TABLE 1.- TOTAL ENERGY FACILITIES<sup>1</sup>

Facility and location	Number of apartments	Prime movers, number and type	Heat-recovery method	Generating capacity, kW	Air-conditioning method
Meadowlark Kansas City Kansas	500	Four gas engines (Cummins)	Steam from engine	1 100	Absorption
Indian Creek Johnson County Kansas	42 500	Five gas engines (Fairbanks/Morse)	Hot water from engine	6 400	Absorption
Georgetown Merriam Kansas	400	Two gas engines (Caterpillar)	Steam from engine	900	Absorption
Villa Media Overland Park Kansas	500	Three gas engines (Baukusa)	Steam from engine	1 050	Absorption
Wingate Indianapolis Indiana	1 200	Eight engines (Caterpillar)	Steam from engine	3 600	Absorption
Co-Op City New York New York	15 400	One steam turbine	None	( <sup>2</sup> )	Centrifugal
Rochdale Village New York New York	5 840	Two steam turbines (Westinghouse) Two dual-fuel engines (Worthington)	None	19 500	Absorption (bleed steam from turbine)
Twin Pines New York New York	5 940	Three dual-fuel engines (Nordberg) Two steam turbines (General Electric)	Steam from engines exhaust	17 000	Centrifugal

<sup>1</sup>Hot and chilled water was used in the heating and cooling systems of all the total energy facilities.<sup>2</sup>Only 50 units have been completed.<sup>3</sup>Capacity of turbine is 7500 kVA, but village uses purchased power.

TABLE II.- THERMAL CONTROL TECHNOLOGY

Process	Principle	Operational characteristics	NASA use
Heat pipes	The enclosure contains an internal capillary wick structure and a liquid in equilibrium with its vapor phase. The liquid evaporates at the hot end of the pipe (evaporator), while the vapor flows to the cold end of the pipe (condenser) and condenses. The condensate is then pulled back to the evaporator by the capillary action of the wick.	The heat pipes operate nearly isothermally, have high thermal efficiencies, have no moving parts, and are highly reliable. Design is constrained by gravity, and variable conductance control is a problem.	Heat pipes are used in the orbiting astronomical observatory and application technology (ATS-E) satellites. Variable conductance, constant-temperature heat pipes, and heat pipes for low-temperature (311 K (100° F)) and high-temperature (422 K (300° F)) radiators for large systems (100 kW) are being investigated by NASA.
Insulations	High-performance insulation is used to reduce the structural heat leak to the extreme space environment. Use of insulation requires a vacuum environment pressure of less than $10^{-4}$ torr.	Heat lost: $3.15 \text{ W/m}^2$ (1 Btu/hr ft <sup>2</sup> ) Weight: $0.26 \text{ kg/m}^2$ (0.05 lb/ft <sup>2</sup> ) (polyester film 3.175 micrometers (1/8 mil)) Weight: $0.85 \text{ kg/m}^2$ (0.18 lb/ft <sup>2</sup> ) (polyimide film 12.7 micrometers (1/2 mil))	A high-performance insulation system was used on Apollo and Skylab spacecraft. The NASA is developing insulation panels that maintain stable thermal properties for 10 years or more and reduce the heat loss by 50 percent.
Thermal coatings	Coatings are surface materials that maintain the required thermal-radiative characteristics (solar absorptance and infrared total hemispherical emittance) by causing the various surface areas to absorb and emit selected amounts of thermal energy.	Coatings provide thermal control of a spacecraft in a vacuum environment.	Coatings are used on all spacecraft for hot, cold, and vacuum environments. The NASA is developing stable low alpha/epsilon radiator coatings.

TABLE III.- THERMAL ENERGY DISSIPATION

Process	Principle	Operational characteristics	NASA use
Radiators	Thermal energy is rejected from a surface that has high emissivity (approximately 0.9) and low solar absorptivity (approximately 0.2) by a pumped fluid circulating through finned tubes attached to the radiating surface. Solar absorbers (black-body radiators) collect solar thermal energy by radiation using materials with low emissivity (approximately 0.2) and high solar absorptivity (approximately 0.98) properties.	Current concepts are discussed in table IV. Materials (e.g., wax) are used to store thermal energy. A pumped fluid circuit may be used to transfer the energy to a heat sink.	Previous NASA experience is discussed in table IV. Modular radiator panels that have a demonstrated load range of approximately 200/l and a capacity for stagnation control are in the development process at JSC. A hybrid concept of using a high-heat and a low-heat capacity fluid is also being studied. The NASA has investigated concepts for use of these radiators on space stations.
Fluid circuits	Thermal energy is transferred from one location to another by pumped fluids.	Fluids with good heat transfer characteristics that are non-toxic and noncorrosive are desirable.	Commercial refrigerant (ethylene glycol) and water circuits have been used during the Gemini and Apollo Programs. The NASA has used many refrigerant fluids including Coolanol, FC-75, and fluorocarbons that are used commercially and has developed the necessary components (e.g., pumps, accumulators, valves, etc.) to pump the fluid.
Thermoelectricity	The Peltier effect of n- and p-type semiconduction is used in coolers. When a current is supplied to two dissimilar metals, heat is transported from the low-temperature junction to the higher temperature radiator.	The use of thermoelectricity provides excellent reliability (no moving parts), but there is no utilization of waste heat. Efficiency of the system drops rapidly with increasing temperature rise per stage or increased number of stages. The system requires high power.	The use of thermoelectricity has been limited. Units with a capacity greater than 1800 kilograms (2 tons) are being developed commercially.

TABLE III.- THERMAL ENERGY DISSIPATION - Concluded

Process	Principle	Operational characteristics	NASA use
Vapor compression	Fluid absorbs heat, vaporizes, is compressed, rejects heat, changes from gas to liquid in condenser, and is throttled to a lower pressure by an expansion valve. External power is provided by a mechanical compressor.	An abundant supply of power is required. Waste heat is not used unless it is combined with a power cycle.	This process is widely used in home and commercial applications including aerospace (KB-70, DC-8, and Convair 440). A prototype unit was developed by NASA for lunar surface and spacecraft applications.
Vapor absorption	In the two-pressure, heat-operated cycle, a vaporizable liquid is used as the refrigerant, and a second liquid that has a high affinity for the refrigerant is used as the absorbent. Heat addition is required for the absorption cycle.	Waste heat is used effectively. Power requirement is low because no compressor is needed. Water solutions such as lithium bromide and water are commonly used.	This process is widely used commercially where waste heat is available, including submarines. A laboratory model of a gravity-independent unit is being tested for NASA.
Vapor absorption	Solids with a large surface area are exposed to a vapor causing a thin layer of condensed vapor to form on the surface. The amount of vapor adsorbed at a low temperature decreases with increasing temperature; therefore, vapor adsorbed at a low temperature can be driven off at a higher temperature.	Waste heat is used very effectively. There is limited flexibility of fluid and adsorbent selection. This process is a cyclic operation.	Adsorbents (e.g., silica gel and mole sieves) have been evaluated, tested, and used by NASA in systems operated cyclically by using vacuum and heat for desorption.



TABLE IV.- ENVIRONMENTAL CONTROL

Process	Principle	Operational characteristics	NASA use
Ventilation	Air is circulated to provide even flow distribution, to minimize drafts, to eliminate dead air spaces and local buildup of airborne contaminants.	High-speed, centrifugal-flow compressors with axial delivery and low specific speed, centrifugal fans are used in spacecraft. Although the compressors are highly efficient, noise levels are a problem.	Independently located fans and air returning from the air processing equipment provide ventilation in spacecraft. The NASA has conducted test programs on air circulation in rooms and has developed analytical techniques for the design and optimization of low-noise high-efficiency fans. Noise abaters are being used on Skylab to reduce fan noise.
Temperature control			
Sensible heat exchanger	Liquid-to-gas heat exchangers provide heating or cooling of air as the air passes through the coils.	Condensation within the heat-exchanger core should be minimized.	Sensible heat exchangers have been used on Gemini and Apollo spacecraft. Analytical techniques have been developed by NASA for the design, optimization, and off-design analysis of multifluid sensible heat exchangers.
Structural insulations	Insulation in structural walls passively controls room temperature.		This technique has been used on Skylab.
Humidity control			
Condensing heat exchangers	Liquid-to-gas condensing heat exchangers cool the air passing over the coils below the air dew-point temperature.	Particulate filtering of the inlet gas stream and collection of condensate is required.	Condensing heat exchangers have been used on Gemini and Apollo spacecraft. Analytical techniques have been developed by NASA for the design, optimization, and off-design analysis of wet-gas heat exchangers.
Desiccants	A desiccant is a chemical compound capable of adsorbing or reacting chemically with the moisture contained in the air.	Heat is required for desorption. This process is a cyclic operation.	Prototype desiccant systems have been developed and tested by NASA. Compounds used include silica gel, zeolites, and activated alumina.
Condensate collection	Moisture condensed by the dehumidification from the atmosphere is collected. Devices include hydrophobic/hydrophilic surfaces, rotary or vortex generators, and external wick separators.	Collection devices must be continuously wet and are subject to microbial growth.	In the Mercury vehicle, a sponge was used in the gas stream. Centrifugal and integral wick separators were used in the Gemini and Apollo spacecraft. The face wick concept is currently being developed.

TABLE V.- AIR PURIFICATION PROCESSES AND INSTRUMENTATION

Process	Principle	Operational characteristics	NASA use
Odor removal	Odors are removed from the gas stream by adsorption on activated charcoal.	Activated charcoal is an effective adsorbent for many organic materials including hydrocarbons.	Odor control was used on Mercury, Gemini, and Apollo spacecraft. The NASA is developing regenerable charcoal concepts.
Catalytic oxidation	Low-molecular-weight compounds can be removed from an air-stream by oxidation over a palladium on alumina catalyst operating above 561 K (530° F).	Catalytic oxidation requires special sorbents for various compounds that cannot be oxidized; it also requires electrical power.	The NASA has developed and tested various experimental models. Similar units have been used on submarines and aircraft.
Sorption	High-molecular-weight compounds can be removed from an air-stream by sorption. Materials that can be used include lithium hydroxide and copper sulfated sorbents.	Sorption is used to remove gases formed in the catalytic oxidation process.	Prototype units have been developed and tested by NASA.
Gas chromatograph	Helium is used as a carrier gas in this multicolumn instrument. The gas sample separates its constituents within the columns, and a detector indicates the concentration. The time required for the constituent to enter the detector indicates which constituent is present.	The detector output is proportional to the partial pressure of each constituent.	A prototype unit is being developed by NASA.
Carbon dioxide sensor	This sensor is an electrochemical (pH) sensing element.	Range: 13 to 4000 pascals (0.1 to 33 mmHg) Temperature: 275 to 322 K (35° to 120° F) Operating life: 3000 hours	The sensor has been used on the Apollo life-support system.

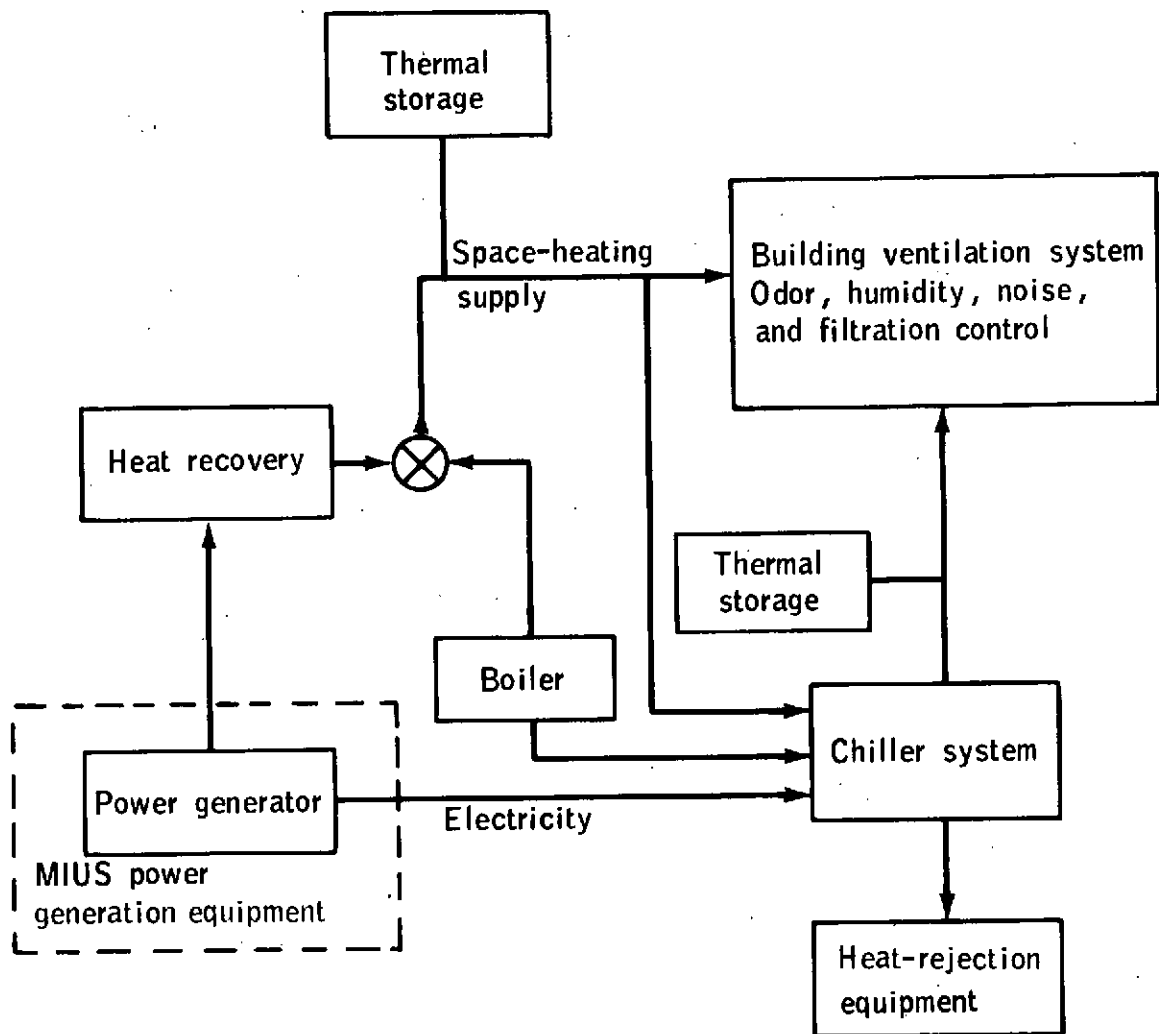


Figure 1.- Block diagram of the MIUS HVAC.

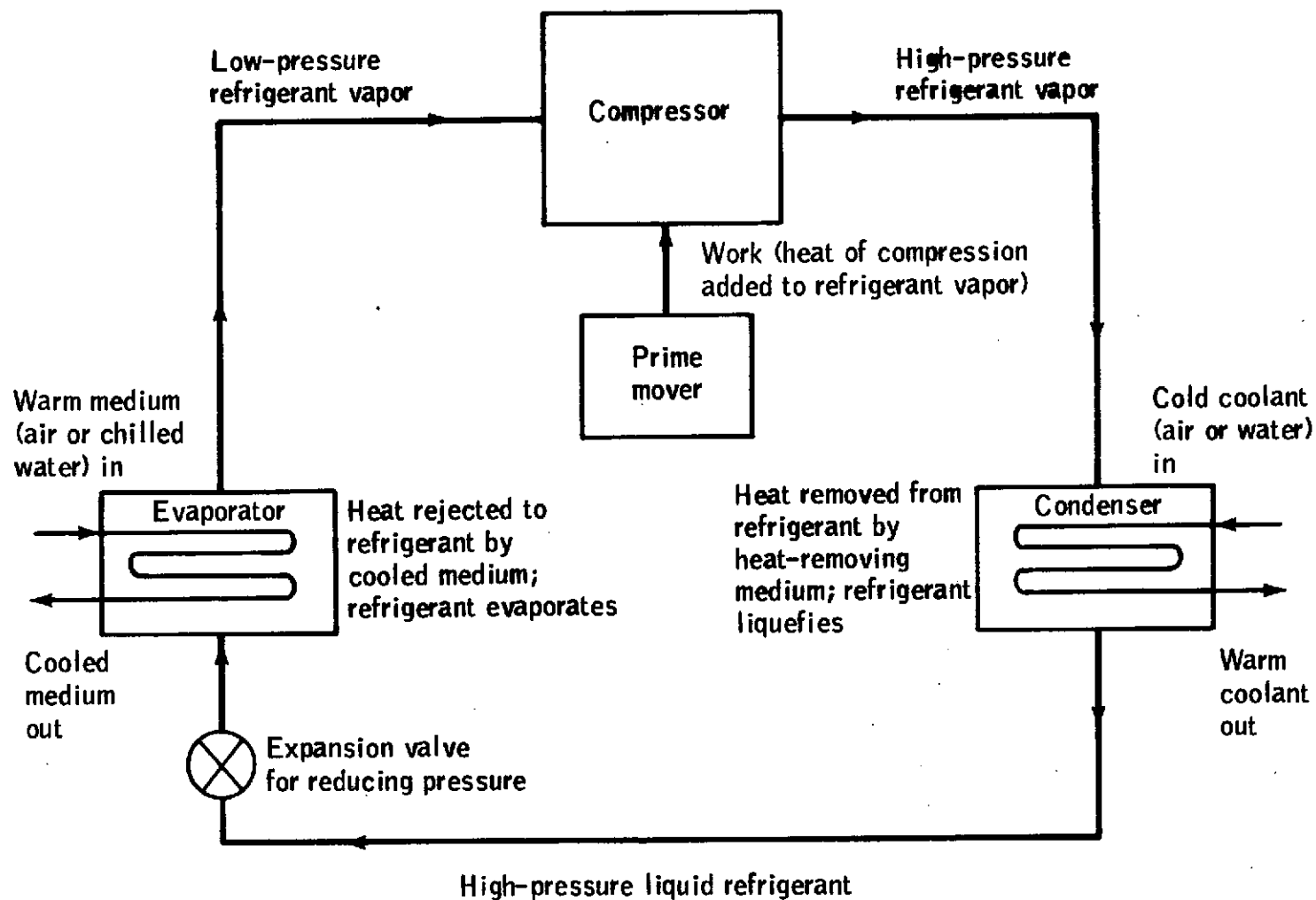


Figure 2.- Vapor compression cycle block diagram.

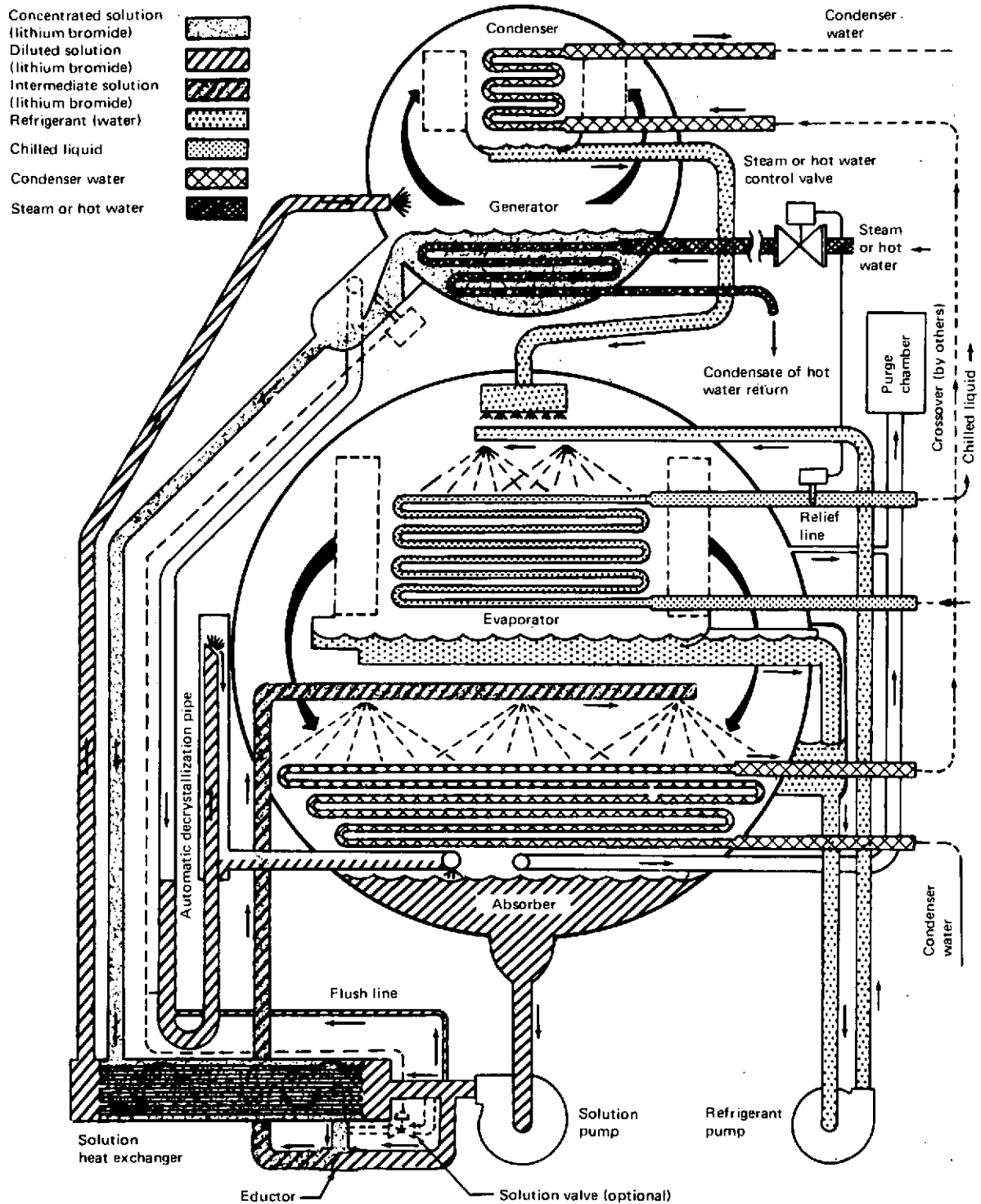


Figure 3.- Schematic of basic absorption cycle.

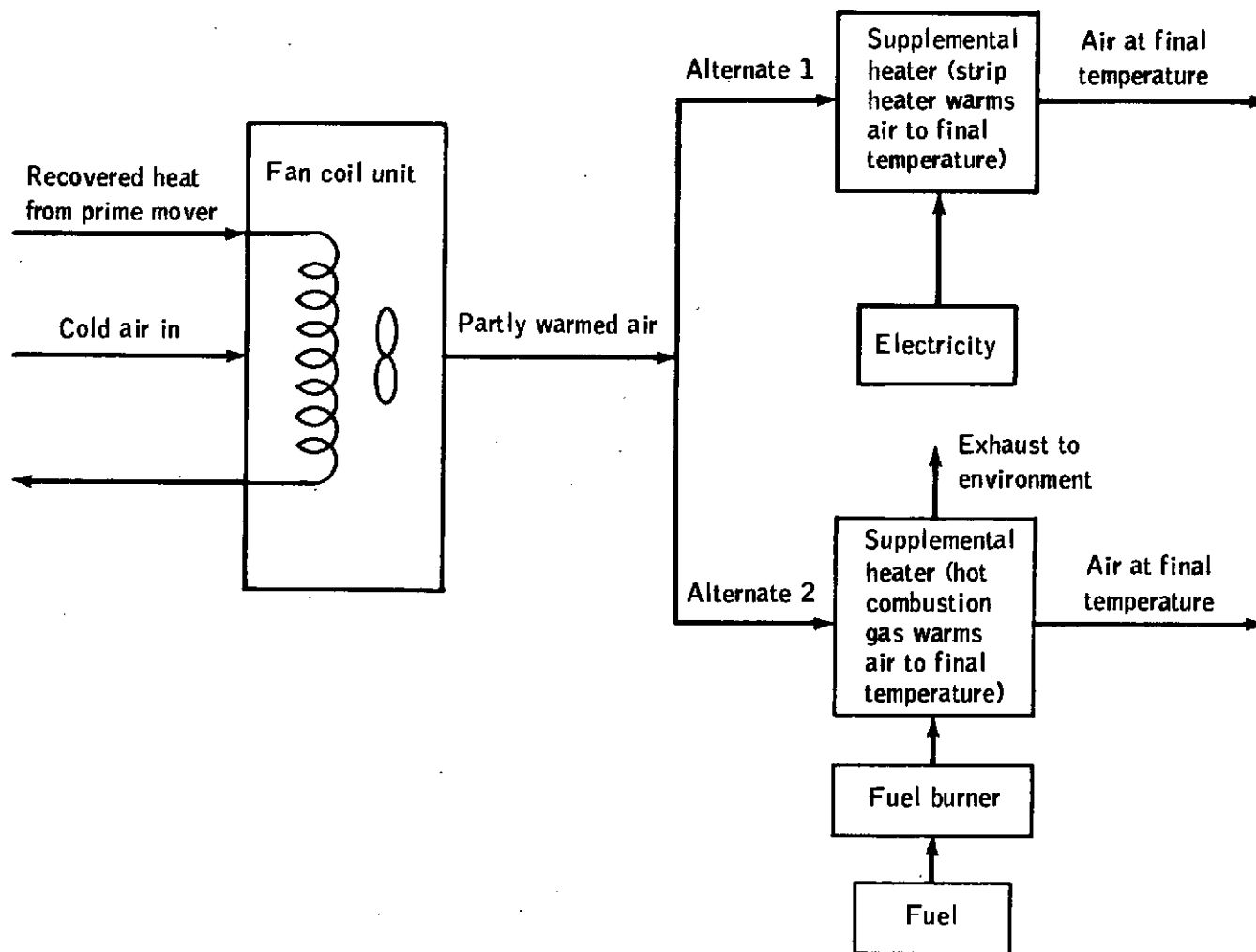


Figure 4.- Building complex supplemental heating block diagram.

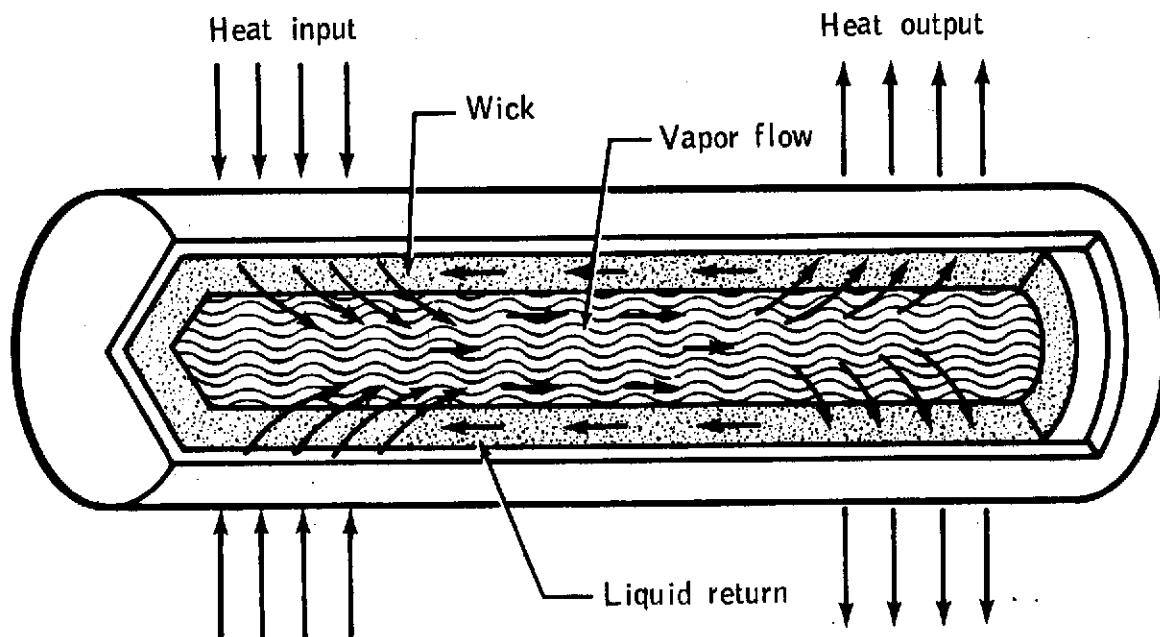


Figure 5.- Schematic of heat pipe.